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NRL-USRD Series F42 Omnidirectional Standard Transducers

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A series of omnidirectional reference transducers for the frequency ranges from 1 Hz to 200 kHz when used as a hydrophone and from 2 to 200 kHz when used as a projector has been developed by the Naval Research Laboratory's Underwater Sound Reference Detachment in Orlando, Florida. The sensitive elements are all piezoelectric lead zirconate — lead titanate PZT-4 hollow spheres encapsulated in polyurethane.

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CONTENTS

NRL-USRD SERIES F42 OMNIDIRECTIONAL STANDARD TRANSDUCERS

INTRODUCTION

The NRL/USRD series F42 transducers were developed to fill the need for calibrated standards with omnidirectional radiation patterns to 100 kHz. The F42 series of transducers consists of four models: A, B, C, and D shown in Fig. 1. They are omnidirectional within ±0.5 dB in the horizontal (XY) and vertical (XZ) planes to 40 kHz for Model A, 50 kHz for Model B, 90 kHz for Model C, and 160 kHz for Model D.

The sensitive elements of the four models are all piezoelectric lead zirconate-lead titanate PZT hollow spheres with the entire spheres encapsulated in polyurethane.

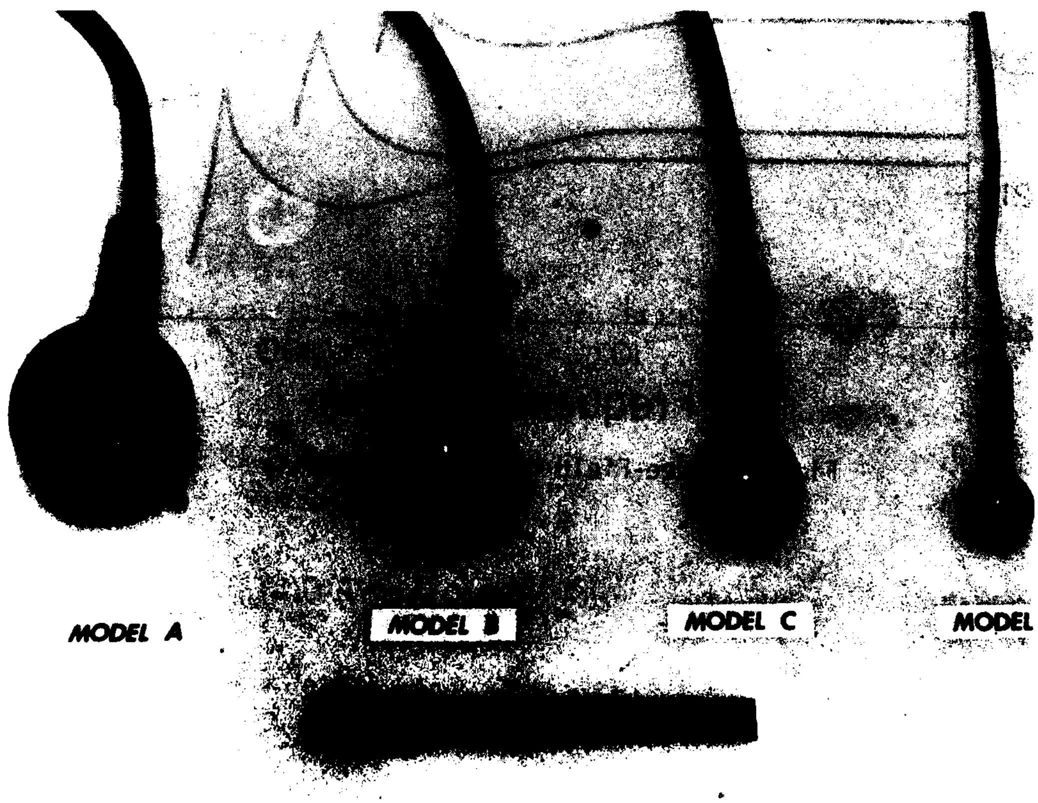

Fig. 1 - Series F42 Transducers

Note: Manuscript submitted February 27, 1979.

The F42 series produce an undistorted source level that is linear with driving voltages up to 400 V(rms) in their useful frequency ranges of 1 to 35 kHz for Model A, 2 to 40 kHz for Model B, 4 to 70 kHz for Model C, and 6 to 160 kHz for Model D. The free-field voltage sensitivity is shown in Fig. 2. Below resonance in the flat portion of the response curve, the sensitivity measured at the end of the specified cable lengths is nominally -194 dB re 1 V/μPa for Model A, -197 dB re 1 V/μPa for Model B, -206 dB re 1 V/μPa for Model C, and -208 dB re 1 V/μPa for Model D.

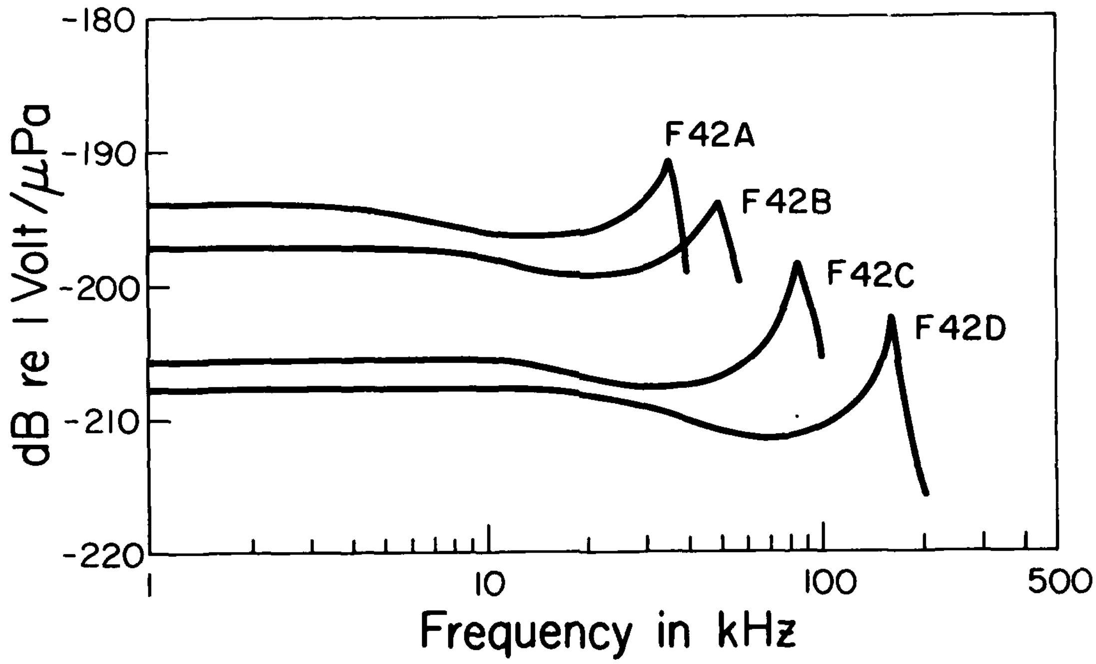

Fig. 2 - Free-Field Voltage Sensitivity

I. DESIGN CONSIDERATIONS

The need for broadband transducers (projectors and receivers) with omnidirectional patterns led to the development of the USRD F42 type transducer. The hollow sphere was chosen as the sensitive element to obtain omnidirectional response characteristics in both the XY and XZ planes and to provide simplicity of design, coupled with good sensitivity.

Four different ceramic spheres were chosen to give the highest sensitivity possible consistent with omnidirectional characteristics for each particular frequency range. Figure 3 shows the typical transmitting voltage response for all four models. Model A is omnidirectional only to 40 kHz whereas Model D is omnidirectional to 160 kHz. A trade-off between sensitivity and the highest frequency requirement must be made in selecting the model to be used.

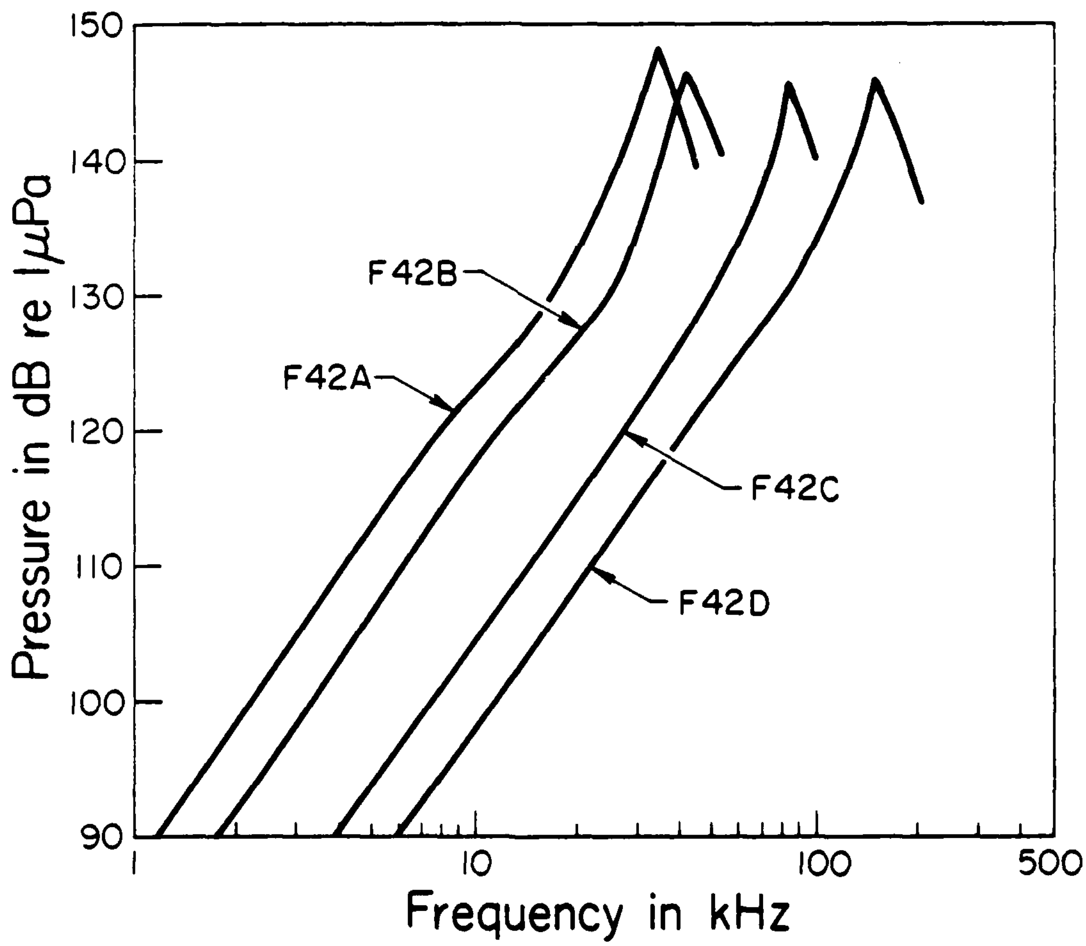

Fig. 3 - Typical Transmitting Voltage Response

Lead zirconate-lead titanate PZT-4 was chosen as the sensor element material because of its high resistance to depolarization and low dielectric losses for high-voltage drive levels. Its temperature stability and high resistance to depolarization under mechanical stress make it suitable for deep-submersion acoustic transducers.

Each model is encapsulated with PRC1538 polyurethane compound. Polyurethane offers a rho-C near that of water over a limited temperature range for a minimum of transmission loss while acoustically coupling the sensor element to the water. It bonds well to the ceramic material and is abrasive resistant, which is important for field use. Although the water permeability of polyurethane is high, the spherical configuration makes it possible to maintain a high resistivity between the electrodes.

The cable, Fig. 4, used on Models A, B, and C is type DSS-2, since it offers good dielectric characteristics for the high voltage levels to which these transducers can be driven. In order to achieve omnidirectional pattern characteristics in the XZ plane for Model D, a smaller cable, Belden 8420 which has a lower dielectric strength, was used. This cable is sufficient since Model D is not normally subjected to very high drive levels.

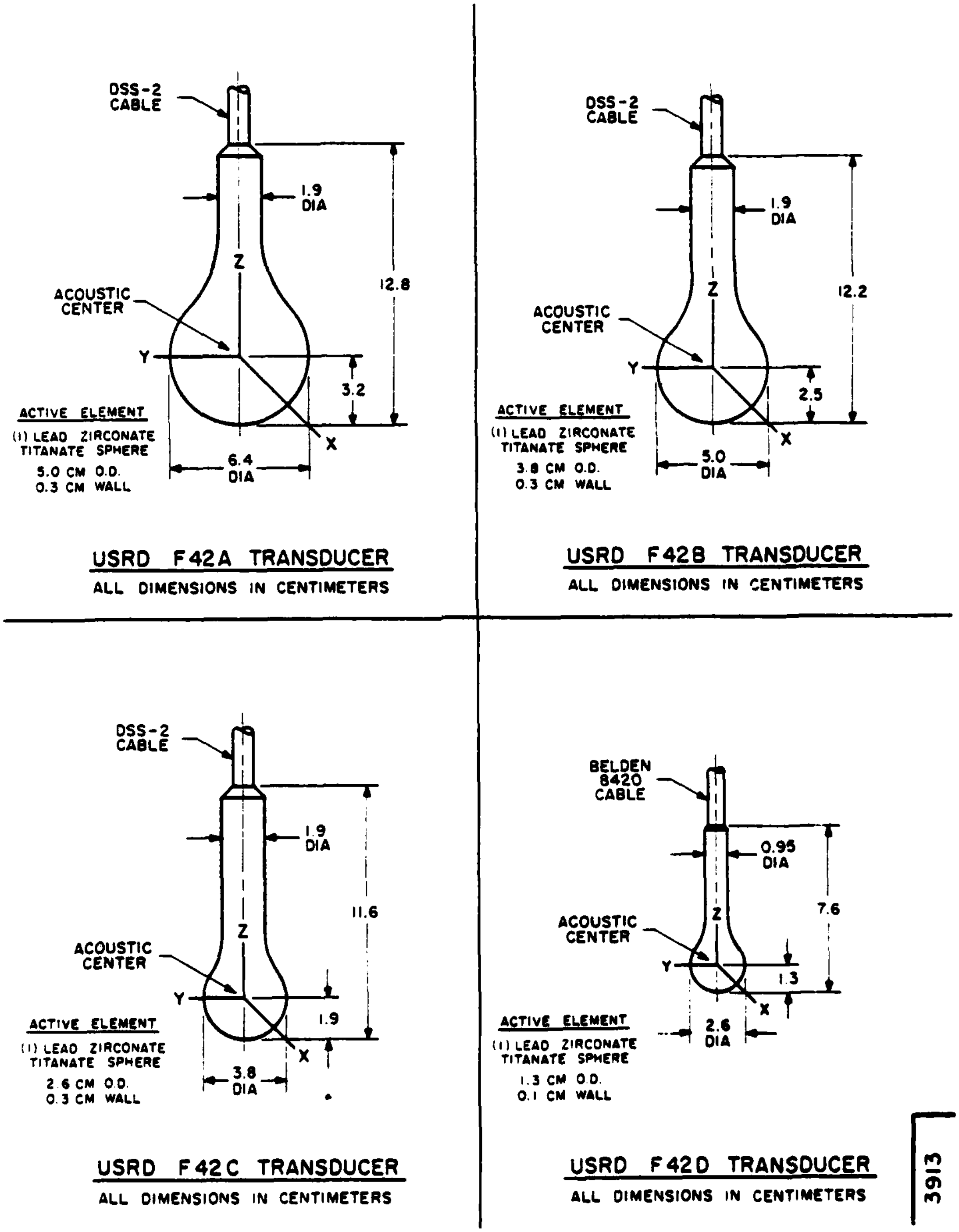

Fig. 4 - Transducer Dimensions

II. CONSTRUCTION

A. Sensitive Element

The sensitive elements of the four F42 models are all piezoelectric lead zirconate-lead titanate PZT hollow spheres. Each sphere consists of two hemispheres epoxied together with EPON VI cement and electrically connected in parallel. The inner electrical lead, which is the high side of the sensitive element, electrically connects both hemispheres together and is brought out through a small hole between the hemispheries, the EPON VI cement seals the hole. Both the inner and outer leads are soldered to the silver electrodes with tin/lead solder containing a small amount of silver.

B. Encapsulating Characteristics

The entire sphere is encapsulated with PRC1538 black polyurethane. The polyurethane has good acoustic characteristics and therefore offers an excellent coupling medium between the sphere and the water. When the ceramic is thoroughly cleaned and degreased, the cured polyurethane will adhere to it so well that the transducer can be subjected to many temperature and static pressure cycles with no indications of bond failure. All metal parts are primed with a special primer, but no primer is necessary on the ceramic silver electrode. The polyurethane encapsulant after cure is tough. Under normal usage it will not break, tear, or stretch and offers excellent protection for the sensor element.

C. Cable Assembly

The electrical cable is terminated at the transducer by a copper ferrule swaged to the cable. The ferrule gives strength to the transducer for either hanging it by the cable or by clamping a rigging fixture around the neck. An excellent bond is obtained between the polyurethane and copper ferrule to ensure a watertight cable seal. The copper ferrule is used in Models A, B, and C but not in Model D, since it is basically a high-frequency transducer and the copper ferrule acoustically interferes with the response. The male portion of an underwater connector, shown in Fig. 5, is molded to a 0.5 meter cable connected to the transducer. The mating connector is usually molded to a 30-m cable, but other lengths can be used if required.

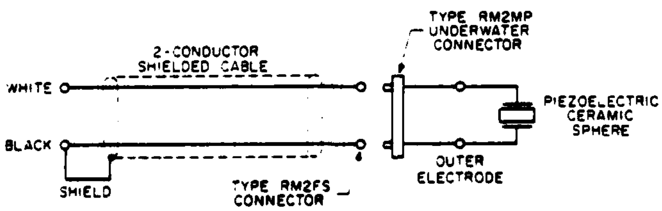

Fig. 5 - Wiring Diagram

III. THEORETICAL CONSIDERATIONS

A. Receiving Sensitivity

The free-field voltage sensitivity of a piezoelectric ceramic hollow sphere can be computed from the relation [1]

$$\frac{V}{P_o} = \frac{b}{c^2+c+1}\left[g_{33}\left(\frac{c^2+c-2}{2}\right) - g_{31}\left(\frac{c^2+c+4}{2}\right)\right] \qquad (1)$$

where V is the open-circuit output voltage developed by the sensor, P_o is the external pressure in newton/meter^2, c = a/b and a and b in meters are the inner and outer radii respectively of the sphere, and g_{33} and g_{31} are the electromechanical constants of the ceramic material in volt meters per newton. The physical constants for the F42 series are shown in Table 1. When these appropriate constants are substituted in Eq. (1), computed sensitivities become -192.05 dB re 1 V/μPa for Model A, -194.70 dB re 1 V/μPa for Model B, -199.2 dB re 1 V/μPa for Model C, and -205.0 dB re 1 V/μPa for Model D.

Table 1 - Physical Constants

	MODEL A	MODEL B	MODEL C	MODEL D
Outside radius (b)	2.5×10^{-2}m	1.91×10^{-2}	1.27×10^{-2}m	6.4×1.0^{-3}m
Inside radius (a)	2.18×10^{-2}m	1.59×10^{-2}m	$.950 \times 10^{-2}$m	5.4×10^{-3}m
g_{33} (PZT4)	26.1×10^{-3}	26.1×10^{-3}	26.1×10^{-3}	26.1×10^{-3}
g_{31} (PZT4)	-11×10^{-3}	-11×10^{-3}	-11×10^{-3}	-11×10^{-3}

$P_o = 1 \times 10^3$ kg/m^3

$K_{33}^T = 1300$

$\varepsilon_o = 8.85 \times 10^{-12}$ farads/meter

$\omega^2 = (2\pi f)^2$ = at 10 kHz = $3.9 \times 10^9 \frac{1}{sec^2}$

These response levels are virtually flat to the frequency at which the sensor element size approaches that frequency's wavelength. A constant receiving sensitivity can be expected up to approximately 5 kHz for Model A, 10 kHz for Model B, 20 kHz for Model C, and 30 kHz for Model D, as shown in Fig. 2.

B. Diffraction

The drop in response between the flat portion of each curve and the resonance peak is caused by the diffraction effect. The value of the diffraction depends on the hydrophone's shape, size, and wavelength. The effect of diffraction as developed for a sphere by Henriquez [2] can be computed from the relation

$$D = [(ka)^2+1]^{-\frac{1}{2}} \tag{2}$$

where D is the diffraction constant and is the average blocked pressure acting on the transducer to the free-field pressure, $k = \omega/c$ where $\omega = 2\pi f$, c is the speed of sound in the medium, and a is the radius of the sphere. When the appropriate values for each of the F42 sensor diameters (Table 1) along with specified frequencies were substituted into Eq. (2), computed points showed that the sensitivity decreases due to diffraction by 3.3 dB at 10 kHz for Model A, by 5.5 dB at 20 kHz for Model B, by 5.5 dB at 30 kHz for Model C, and by 4.4 dB at 50 kHz for Model D. Comparing these computed values to the measured responses shown in Fig. 2 indicates less deviation in the free-field voltage sensitivity in all four models than the computed values. This is due largely to the natural resonance of the sensor elements counteracting the diffraction effect and holding the response level up.

C. Transmitting Response

The transmitting voltage response [3] (TVR) is

$$(TVR) = \frac{V}{P_o} / JZ \tag{3}$$

where $\frac{V}{P_o}$ is the receiving sensitivity, J the reciprocity parameter equals $\frac{2d}{P_o f}$, d is the radial distance from the source, P_o is the density of the medium, and f is the frequency where $|Z| = \frac{1}{\omega C}$ and $\omega = 2\pi f$, where

$$C = 4\pi\varepsilon_o K_{33}^T \frac{ab}{b-a} \tag{4}$$

is the electrical shunt capacitance of the sphere, ε_o is the dielectric constant of free space, K_{33}^T the dielectric constant of the ceramic material, and a and b are the inner and outer radii of the sphere.

Substituting Eq. (1) into Eq. (3) results in the relation for the TVR (pressure per volt at 1 m) for a sphere

$$TVR = \frac{ab^4\omega^2 P_o \varepsilon_o K_{33}^T}{b^3 - a^3}\left[g_{33}\left(\frac{c^2 + c - 2}{2}\right) - g_{31}\left(\frac{c^2 + c + 4}{2}\right)\right] \tag{5}$$

When the appropriate constants shown in Table 1 are substituted into Eq. (5). computed TVR levels at the specified frequencies become 125 dB re 1 μPa/V for Model A, 116 dB re 1 μPa/V for Model B, 105.4 dB re 1 μPa/V for Model C, and 97.9 dB re 1 μPa/V for Model D. These computed values are in close agreement with the measured responses at 10 kHz, shown in Fig. 3. Diffraction affects the transmitting response as it does the receiving response and can be computed from Eq. (2). Therefore, when the TVR level is computed at a specified frequency, the diffraction constant equation should be applied to determine any diffraction effect. After one point of the TVR below the diffraction effect is computed using Eq. (5), the remainder of the response below resonance can be computed from that point by the relation TVR $\approx \omega^2$, and the TVR changes 12 dB per octave. This occurs because the impedance is entirely capacitive reactance and the sphere is small compared to its wavelength. The TVR at resonance can be predicted by combining the sphere's radiation impedance and directivity factor with the diffraction constant.

D. Directivity

A sphere with radial polarization and displacement is theoretically omnidirectional both as a receiver and a transmitter in both the XY and XZ planes. As a projector, this means that all displacements eminating from the sphere are in phase. In practice, the directivity pattern will deviate from being omnidirectional at the frequency where the sphere size approaches the wavelength or near resonance. This is caused in part by nonuniformity in polarization of the spheres, nonuniformity of the wall thickness as well as the OD and ID dimensions, the discontinuity when two hemispheres are epoxied together, and proximity of the cable gland assembly.

IV. OPERATING CHARACTERISTICS

A. Orientation

The F42 transducers are oriented as a sphere in the left-handed coordinate system defined in "American Standard Procedures for Calibration of Electroacoustic Transducers, Particularly Those for Use in Water, Z24.24-1957," and shown in Fig. 4. The geometrical center of the sensitive element is at the origin of the coordinates; the longitudinal axis coincides with the Z axis. The encapsulating mold seams are used as zero reference marks in both the X and Z axis planes.

B. Directional Characteristics

The F42 transducers are omnidirectional within ±0.5 dB in the XY and XZ planes to 40 kHz for Model A, 50 kHz for Model B, 90 kHz for Model C, and 160 kHz for Model D.

C. Free-Field Voltage Sensitivity Response and TVR

Figure 2 shows the typical free-field voltage sensitivities at the end of the indicated cable lengths. The responses of all four models are plotted on this figure.

Figure 3 shows the typical measured TVR of the four models. Here, as with the receiving response, the diffraction effect occurs in the transmitting response. Below resonance, the diffraction effect in the transmitting response is a reciprocal of the diffraction effect in the receiving response in the same relationship as the patterns are reciprocal.

D. Impedance

The electrical motional impedance of the F42 series transducers measured in water under free-field conditions is shown in Fig. 6. The measurements were made with a wide frequency range, Drantz impedance bridge, with the low terminal connected to the shield and grounded (unbalanced). For impedance matching information, the total impedance can be computed from the resistance on the horizontal scale and the reactance in the vertical scale. Notice that the resonant frequencies as indicated on the motional loop do correspond with resonant peaks as shown in the response curves, Fig. 2.

V. CONCLUSIONS

This report has described the construction and operation of the USRD F42 series transducers, shown in Fig. 1. This series offers omnidirectional characteristics both as receivers and as projectors for the frequency range 1 Hz to 200 kHz.

ACKNOWLEDGMENTS

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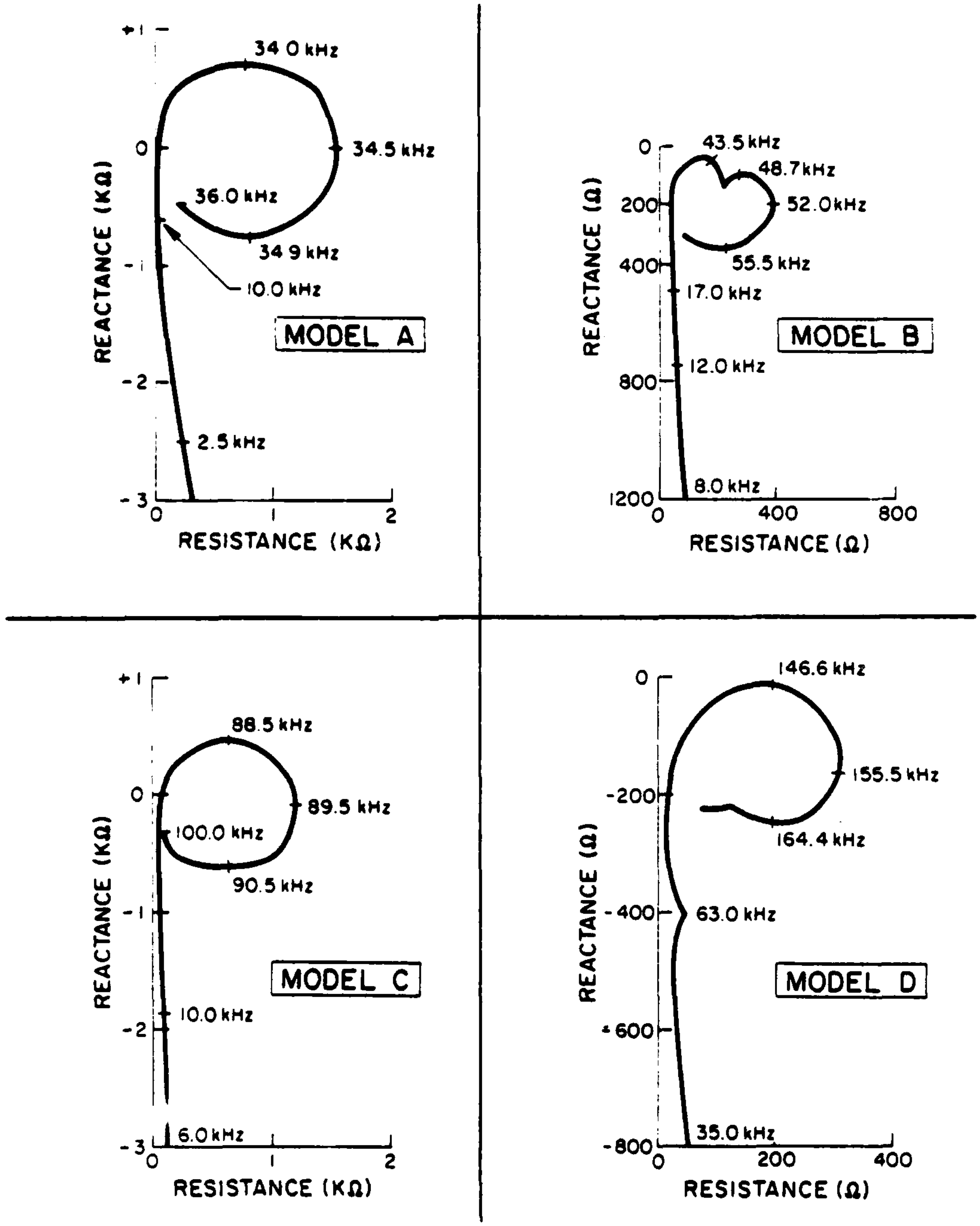

Fig. 6 - Typical Impedances